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CASE STUDY

Comparative life cycle assessments of incineration and non-incineration treatments for medical waste

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Abstract
Background, aim, and scope Management of the medical waste produced in hospitals or health care facilities has raised concerns relating to public health, occupational safety, and the environment. Life cycle assessment (LCA) is a decision-supporting tool in waste management practice; but relatively little research has been done on the evaluation of medical waste treatment from a life cycle perspective. Our study compares the environmental performances of two dominant technologies, hazardous waste incineration (HWI) as a type of incineration technology and steam autoclave sterilization with sanitary landfill (AL) as a type of non-incineration technology, for specific medical waste of average composition. The results of this study could support the medical waste hierarchy.
Materials and methods This study implemented the ISO 14040 standard. Data on steam autoclave sterilization were obtained from an on-site operations report, while inventory models were used for HWI, sanitary landfill, and residues landfill. Background data were from the ecoinvent database. The comparative LCA was carried out for five alternatives: HWI with energy recovery efficiencies of 0%, 15%, and 30% and AL with energy recovery efficiencies of 0% and 10%.
Results The assumptions on the time frame for landfill markedly affect the impact category scores; however, the orders of preference for both time frames are almost the same. HWI with 30% energy recovery efficiency has the lowest environmental impacts for all impact categories, except freshwater ecotoxicity. Incineration and sanitary landfill processes dominate global warming, freshwater aquatic ecotoxicity, and eutrophication of incineration and non-incineration alternatives, respectively. Dioxin emissions contribute about 10% to human toxicity in HWI without energy recovery alternatives, and a perturbation analysis yielded identical results. As regards eutrophication, non-incineration treatments have an approximately sevenfold higher impact than incineration treatments.
Discussion The differences between short-term and long-term time frame assumptions mainly are decided by heavy metals dissolved in the future leachate. The high heat value of medical waste due to high contents of biomass, plastic, and rubber materials and a lower content of ash, results in a preference for incineration treatments. The large eutrophication difference between incineration and non-incineration treatments is caused by different N element transformations. Dioxin emission from HWI is not the most relevant to human toxicity; however, large uncertainties could exist.
Conclusions From a life cycle perspective, the conventional waste hierarchy, implying incineration with energy recovery is better than landfill, also applies to the case of medical waste. The sanitary landfill process is the key issue in non-incineration treatments, and HWI and the subsequent residues landfill processes are key issues in incineration treatments.
Recommendations and perspectives Integrating the medical waste hierarchy and constructing a medical waste frame-

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work require broader technologies to be investigated further, based on a life cycle approach.

Keywords Comparative LCA · Hazardous waste incineration · Landfill · LCA · Medical waste · Special health care waste · Special hospital waste · Steam autoclave sterilization

1 Background, aim, and scope

Medical waste, also called special hospital waste or special health care waste, refers to waste streams generated by hospitals or health care facilities and containing infectious, pathological, or radioactive fractions. In most countries, medical waste is regulated or defined as a form of hazardous wastes by laws or directives, such as the European Waste Category (European Communities 2000), the Medical Waste Tracking Act in the US (USEPA 1988), Hazardous Waste Regulations in the UK (UK Statutory Instrument 2005), and the National Catalog of Hazardous Wastes in China (SEPA 1998), requiring special collection, treatment, and disposal. The treatment technologies for medical waste, excluding radioactive waste, could be categorized into two types: (1) incineration technologies, e.g., cement incinerator, rotary kiln incinerator, or pyrolysis incinerator, and (2) non-incineration technologies, e.g., autoclave, microwave disinfection, and plasma disinfection. The issue of environmental pollutions relating to these two categories has been discussed since the 1980s, especially since dioxins and anthropogenic mercury have been detected in significant amounts in gas and ash from medical waste incinerators (Glasser et al. 1991). Medical waste incinerators are ranked among the top four sources for these two emissions in the US (USEPA 1997; Cleverly et al. 1999). However, incineration is the most frequently used option, due to its advantages regarding the sterilization of pathological and anatomic waste, volume and mass reduction, and energy recovery. According to previous studies (Park and Jeong 2001; Lee et al. 2004), about 49–60% of medical waste is treated by various incinerations, 20–37% by autoclave sterilization, and 4–5% by other methods. Incineration and steam autoclave sterilization are the main methods currently being used and are considered mature technologies.

Waste policy making is generally based on a waste hierarchy. Although different versions of this hierarchy exist, the following order is usually suggested: (1) reduce the amount of waste; (2) reuse; (3) recycle materials; (4) incinerate with energy recovery; and (5) landfill (Finnveden et al. 2005). In medical waste management, the first priority is generally accepted. However, reusing and recycling materials is currently forbidden by regulations due to the high hazardous potential of medical waste. The order of preference regarding incineration and landfill is often discussed. Employing the waste hierarchy for medical waste management raises further questions, e.g., "what is the hierarchy for medical waste treatment?" and "what is the hierarchy for final disposal of medical waste after sterilization processing?"

So far, a large number of analytical tools have been used to compare waste treatment strategies, including cost–benefit analysis, life cycle assessment (LCA), analytic hierarchy process, and combinations of them (Haastrup et al. 1998; Clarke 2000; Eriksson et al. 2005). The European Commission's Strategy on waste and resource highlights the life cycle thinking is important for more sustainable waste management practice. LCA, as a quantitative tool for life cycle thinking, could offer decision makers information about potential environmental burdens caused by different alternatives. Unfortunately, less research has been performed on medical waste than on municipal solid waste (MSW) and biomass waste. The present study therefore evaluated steam autoclave sterilization with sanitary landfill (AL), as the main non-incineration technology, and hazardous waste incineration (HWI) for a specific medical waste composition, from a life cycle perspective. Contribution and perturbation analyses were presented to support the results.

2 Materials and methods

The present study implemented the method of an attributional LCA described in the *Handbook on Life Cycle Assessment* (Guinée et al. 2002), written as a guide to the ISO standard (ISO 2006). The specific aspects are illustrated in detail below.

2.1 Goal and scope definition

The goal of this study is to compare incineration and non-incineration technologies, viz. HWI and AL, for the treatment of medical waste, in terms of environmental performance. The functional unit is defined as to the disposal of 1 ton of medical waste of a specified composition. Medical waste is a non-homogenous mixture of wastes, with different components and amounts in different countries on their medical situation. It is necessary to point out that the term "medical waste" has often been used interchangeably with other terms such as "special hospital waste" and "infectious waste." In this study, "medical waste" refers to potentially infectious waste generated in diagnosis, treatment, examination, or research by health care facilities and research institutions. Characteristics of medical waste in different countries have been examined by previous studies (Kuo et al. 1998; Lee et al

2004; Mohee 2005; Deng 2005). The present study specifically relates to solid medical waste of an average composition, as shown in Table 1, excluding special fractions such as radioactive waste and small fractions such as tissues and drugs. Five alternatives based on these two types of technologies are evaluated. The HWI alternatives include three energy recovery efficiencies based on the lower heating value of medical waste: 0% (without energy recovery), 15% (conventional), and 30% (optimized). The AL alternatives include two situations: 0% (landfill gas ignited on site) and 10% (conventional). Table 2 presents a more detailed description of each alternative.

2.2 Inventory

Ideally, LCA should include each and every flow until its economic inputs and outputs have all been translated into environmental interventions (Guinée et al. 2002). In the present study, several cutoffs and assumptions are used.

- The medical waste is the input of treatment system. The previous chain of producing discarded products is not included. The alternatives treat equal amounts of medical waste of identical composition.
- Collection and transport processes are identical in all alternatives and are cut off since this study is comparative.
- Landfill is assumed to be the ultimate process for all solid-waste streams.

Data for steam autoclave sterilization were derived from an operations report (HYDROCLAVE Systems Corp. 1998). Data for HWI, sanitary landfill, and residues landfill were calculated by inventory models, a series of programs simulating the disposal inventories of specified waste (Doka 2003a, b). These models were not originally developed for medical waste; thus, specific modifications will be illustrated in "Section 4.1." Other background data were taken from the ecoinvent database (ecoinvent Center 2004). Substitution was used as the allocation approach. Electricity produced from energy recovery was assumed to substitute an equivalent flow of the average low-voltage electricity produced in the Netherlands (89.5% fossil, 4.4% nuclear, 3.9% waste, 2.0% renewable, and 0.2% hydro).

Table 1 Average composition of the specific medical wastes studied

Category	Waste fraction	Share	Main sources
Biomass	Mix cardboard	10%	Used cardboard
	Wood	5%	Stick
	Textile	30%	Cotton, bandage
Plastic	Mix plastics	45%	Check instruments, IV bag
Rubber	Natural rubber	5%	Single-use gloves, catheter
Sharp	Inert metal	2.5%	Needle, knife, syringe
Glass	Glass	2.5%	Culture, bottle

Note: composition is calculated by weight
The water content of the specific medical wastes is 20%

Table 2 Alternatives studied

Type	Common feature	Name	Specific feature
Incineration	Hazardous waste incinerator with electricity generation	HWI	Without energy recovery
		HWI15%	Energy recovery efficiency is 15%, conventional
		HWI30%	Energy recovery efficiency is 30%, optimized
Non-incineration	Steam autoclave sterilization with sanitary landfill	AL	Landfill gas ignited on site
		AL10%	With electricity generation from landfill gas Energy recovery efficiency is 10%

2.3 Impact assessment and interpretation

The problem-oriented approach baseline CML1999 (Guinée et al. 2002) was used in impact assessment. Nine impact categories were taken into account: abiotic depletion (AD), global warming (GW), ozone depletion (OD), human toxicity (HT), freshwater aquatic ecotoxicity (FAET), terrestrial ecotoxicity (TET), photochemical oxidant creation (POC), acidification, and eutrophication.

The interpretation of results was supported by contribution and perturbation analyses. The computations follow the method developed by Heijungs and Kleijn (2001). A contribution analysis identifies those processes or elements that make the highest contributions to a particular emission or category, allowing key problems or improvement potions to be pinpointed. A perturbation analysis identifies sensitive parameters, i.e., whether a small change in an input parameter induces a large change in an impact category. These two analyses were performed at the level of characterization.

3 System descriptions

Hazardous waste incineration system Figure 1 shows the flow chart of the HWI system, which is divided into five processes: HWI, residues landfill, external energy production, ancillary materials production, and infrastructure. The HWI process includes incineration, flue gas cleaning, internal wastewater treatment, and electricity production (in the alternatives with energy recovery). The flue gas

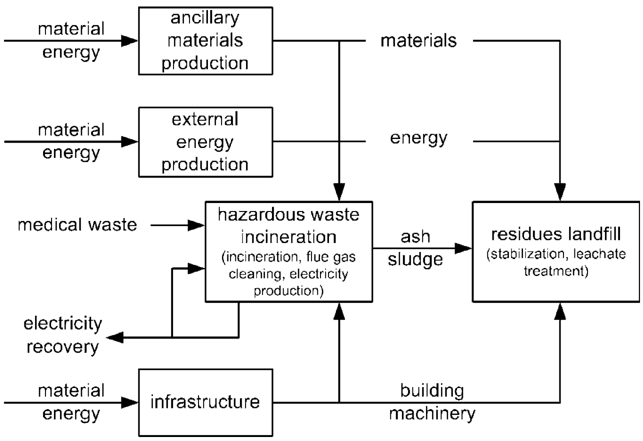

Fig. 1 Flow chart of hazardous waste incineration system

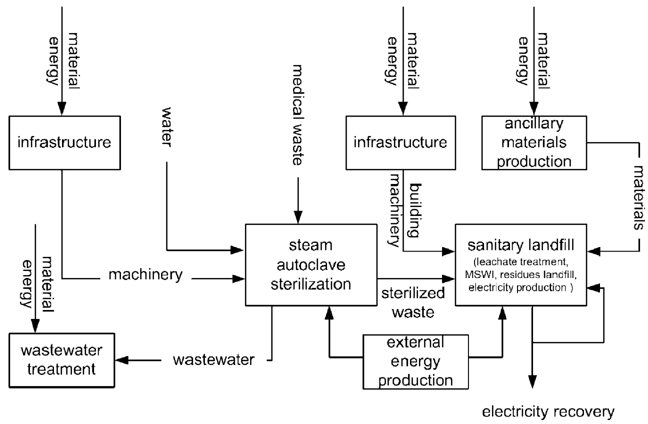

Fig. 2 Flow chart of steam autoclave sterilization with sanitary landfill system

system is made up of a wet scrubber, an electrostatic precipitator, and a $DeNO_x$ reduction stage to remove acids, heavy metals, and NO_x. The electricity generated is fed back into the process, with excess electricity being delivered to the low-voltage grid. The sludge and ash collected from the HWI process are transferred to residues landfill, which involves two main processes: stabilization and leachate treatment. Infrastructure and auxiliary materials processes relate to the HWI and residues landfill processes. The major auxiliary materials consumed are: water for the wet scrubber, NaOH to neutralize acid gas, HCl to adjust pH, natural gas and NH_3 for the $DeNO_x$ stage, $CaCl_2$ to precipitate phosphates in the wastewater treatment, and cement for stabilization in landfill. The external energy used in the HWI system includes fuel oil as a supplementary fuel and electricity for equipments operation.

Steam autoclave sterilization with sanitary landfill system The utility of heat, in particular moist heat, to achieve sterilization for reusable instruments has been used for decades. Recently, this technology has also been adopted for medical waste treatment. Figure 2 shows the flow chart of the AL system. Incoming medical waste is loaded into an autoclave, crushed, pressurized, and heated by the high-temperature steam produced by a steam generator. Medical waste is sterilized by maintaining the desired temperature for a period of time in the autoclave. The discharged water is transferred to wastewater treatment. After being sterilized, the waste fragments regarded as MSW are sent to a sanitary landfill. Sanitary landfill process includes electricity production (in the alternatives with energy recovery), leachate treatment, sludge incineration, and residues landfill. The electricity generated is fed back into the process, with excess electricity being delivered to the low-voltage grid. The infrastructure and auxiliary materials processes are similar to those of the HWI system.

4 Results and discussion

4.1 Life cycle inventory analysis

HWI system The LCI of the HWI system was simulated using the LCI model for the incineration of specific hazardous waste (Doka 2003a). In this model, inventory data are classified into waste-specific and process-specific parameters: waste-specific parameters depend on the character of waste, while process-specific parameters merely depend on process conditions. The most relevant inventory results for the specific medical waste incineration, excluding ash and slag treatment, are presented in the Electronic Supplementary Material. Biogenic CO_2 generated in the incineration process was not taken into account. The residues landfill process, which is similar to a sanitary landfill process, will be discussed in the AL system. The heat value of medical waste is much higher than that of MSW due to its higher contents of biomass, plastics, and rubber materials and lower ash content, resulting in a high potential for energy recovery in HWI. The electricity efficiency estimated by the model is small, as part of the data derive from waste solvents incineration. Our study therefore compared two gross electricity efficiencies: 15% and 30%, representing the conventional and optimized situations, respectively.

Dioxins as well as heavy metals are particularly toxic air emissions generated by medical waste incineration. Dioxins are regarded as process specific, and this study adopts a value of 3 ng toxicity equivalent quotient (TEQ) per kilogram waste. The limit for dioxin concentrations established by European legislation is 0.1 ng TEQ per cubic meter flue gas (European Commission 2000). These two figures are equal, considering the volume of flue gas is 30 m^3 per kilogram waste (Coutinho et al. 2000). However, several studies have shown that dioxins are dependent on

waste composition (European Commission 2000; Coutinho et al. 2000), and "when the emission factors are not associated with the composition of incinerated mixture, its usefulness is very doubtful," as pointed out by Ferraz and Afonso (2003). Compared to other physical and chemical conversions, the mechanisms of dioxin formation are much more complex, and knowledge about them is still scarce. This could not be fixed within the scope of our study. One of the solutions is to resort to numerical approaches, such as perturbation analysis, for more information.

AL system LCI data for autoclave sterilization process were taken from an operations report for two H-100 hydroclaves (HYDROCLAVE Systems Corp. 1998), as shown in the Electronic Supplementary Material. As the process employs a type of low-temperature technology, whose temperature is insufficient to cause chemical change, the airborne emissions from the sterilization process are mainly volatile organic compounds. The following key assumptions were made for inventory analysis:

- The standard operation condition is 30 min of sterilization at 121°C.
- An autoclave has an average installation time of 20 years.
- After sterilization, the volume of waste is reduced by 80% through shredding, and the mass of waste is reduced by 20% through water content evaporation.
- Air emission from the sterilization process is assumed to be process specific due to lack of data.

The LCI of sanitary landfill was calculated using an LCI model (Doka 2003b). The choice of time frame in the landfill model is still subject to debate. The ecoinvent database simulates the landfill process covering 60,000 years, which could introduce large uncertainties due to the absence of empirical long-term emission data from the leachate by an experimental approach. Short-term emissions, i.e., a period of 100 years, is usually used in some waste management models, such as IWM2 (McDougall et al. 2001) and ORWARE (Dalemo et al. 1997). To access the influence of time assumptions, the present study investigated both short-term emissions (100 years) and long-term emissions (60,000 years). We did not take the carbon sink in sanitary landfill into consideration due to the limitation of LCI model used, though it is noted that crediting for trapping biogenic carbon with a limited time perspective is of particular interest (Moberg et al. 2005). Biogenic CO_2 was also neglected. Electricity production from landfill gas was calculated using the assumption that the recovery rate of landfill gas is 53%, and the electricity recovery efficiency is 10% based on the lower heat value of specific medical waste. The most relevant LCI results of landfill for this specific waste are presented in the Electronic Supplementary Material.

4.2 Impact assessment

Figure 3 gives overviews of characterization results, relating to the short-term and long-term time frames, respectively. The HWI alternative has been set at 100%, and other alternatives are presented relative to it. All alternatives yield significantly better HT and FAET scores under the short-term assumption. As regards eutrophication, the non-incineration processes yield better scores than the incineration ones. Under the long-term assumption, the HWI alternative yields the highest scores in all impact categories except TET and eutrophication. HWI 30% invariably has the lowest impact scores. All AL alternatives show high eutrophication values, more than sevenfold higher than those of HWI alternatives. Considering energy recovery from the incineration and sanitary landfill processes, it results in a decrease in all of the impact categories, especially at higher energy recovery efficiency. This is the case for both time frame assumptions. Energy

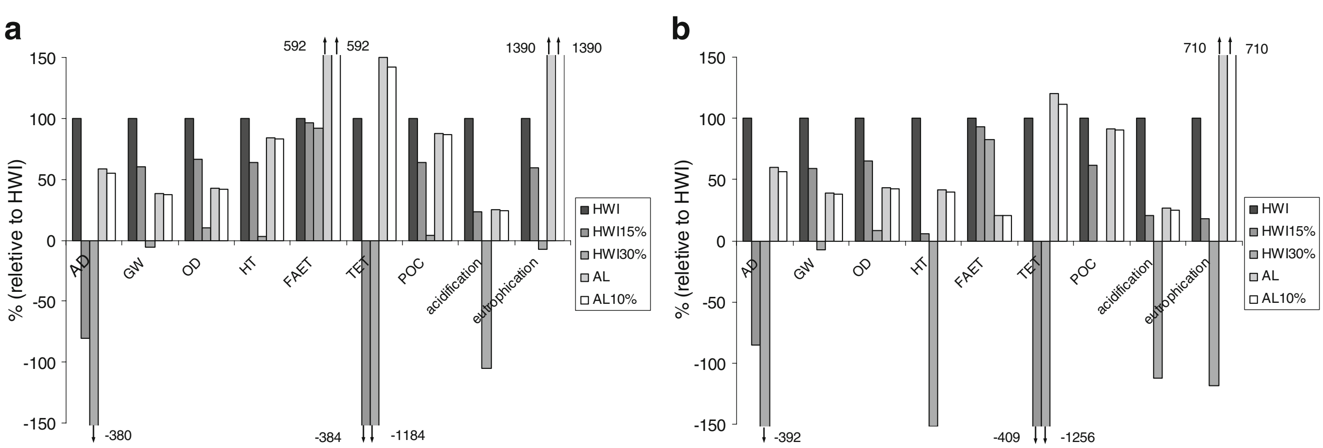

Fig. 3 Overview of characterizing for all alternatives: **a** long-term time frame, **b** short-term time frame

recovery in sanitary landfill only slightly influences all impact categories due to the lower landfill gas collection efficiency and lower conversion efficiency from landfill gas to electricity. Based on the LCI results, the differences between short-term and long-term characterization results are mainly decided by ignoring heavy metals dissolved in the future leachate. Although the time frame assumptions markedly affect the impact category scores, the orders of preference for two time frames are almost the same. The following analysis would result from the conventional assumption, viz. short-term, for both sanitary landfill and residues landfill, which is more acceptable and easier to compare with other case studies. Figure 4 shows the normalized results for all alternatives in the short-term time frame based on the world 95 normalization data. FAET scores of incineration treatments appear much higher than those of others.

The following sections deal with four specific categories in comparison, using the approach of contribution analysis or perturbation analysis. Selected categories are as follows: (1) GW, which indicates the climate change and is one of the serious threats humanity is facing; (2) HT, which may reflect the consequences of variable dioxin emissions; (3) FAET, which appears as an important impact category from the normalization results; and (4) eutrophication, because of the large difference between incineration and non-incineration alternatives.

4.2.1 Global warming

Figure 5 presents the contribution analysis for GW in the aspect of the process. HWI 30% causes the smallest GW, while HWI causes the greatest. Non-incineration alternatives are preferable to HWI 15%. Incineration and sanitary landfill are the dominant sources in incineration and non-incineration alternatives, respectively, followed by external energy consumption. The results of a contribution analysis

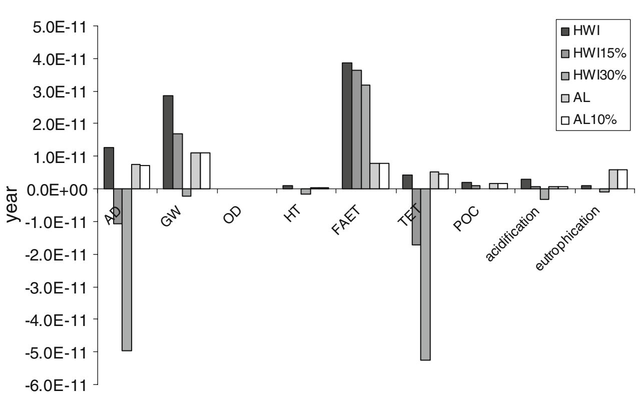

Fig. 4 Normalization results for all alternatives in short-term time frame

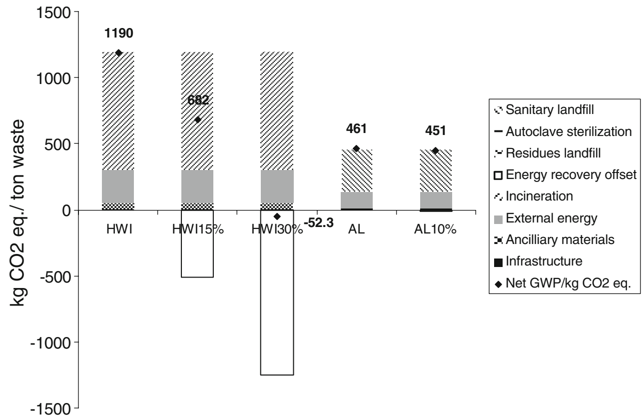

Fig. 5 Contribution analysis for global warming in short-term time frame

based on element flows show about 98% of GW in incineration alternatives comes from CO_2, while, in non-incineration alternatives, 60% comes from CH_4. The ranking of alternatives with respect to GW in this case shows few conflicts with other studies (Wollny et al. 2002; Finnveden et al. 2005) comparing incineration and sanitary landfill. Taking a closer look, three factors may affect the results: biological consumption of waste, energy recovery, and time frame. Incineration is preferable to sanitary landfill for waste with a high content of biogenic carbon since biogenic CO_2 is regarded as neutral, and biogenic carbon in sanitary landfill generates much more methane than in incineration. In this case, 26% of carbon in medical waste is biogenic, which is less than the level of MSW. The efficiency of energy recovery yields a significant change in GW, as shown in Fig. 3. In most cases, GW is lower for incineration when energy recovery is used to replace fossil fuels. Other studies have also pointed out that the sources of avoided fuel (e.g., electricity or heat, from fossil fuels or renewable fuels) have a large influence. The time frame affects the degree of decomposition. A short-term time frame assumes decomposition occurs on the easily degradable materials, after which the rest changes to be inert. A long-term time frame assumes decomposition occurs on all kinds of materials during that time.

4.2.2 Human toxicity and freshwater aquatic ecotoxicity

Medical waste contains large amounts of plastics and chlorinated materials, which are estimated as the main sources of dioxin emission. Table 3 shows the results of contribution analyses for HT and FAET. The HT category is dominated by emissions from residue landfills in incineration alternatives, followed by the emissions from an incineration process. Dioxins contribute 10% of total HT in the short-term time frame and even less than 10% in the

Table 3 HT and FAET contribution analysis results for HWI and AL in short-term time frame

Alternative	HT			FAET		
	Process	Emission	Contribution	Process	Emission	Contribution
HWI	Residues landfill	Antimony[a], to water	26%	Incineration	Nickel[b], to water	48%
	Incineration	Dioxins, to air	10%	Incineration	Copper[b], to water	36%
	Incineration	Nickel[b], to water	7%	Incineration	Zinc[d], to water	2%
	Ancillary material	Chromium VI, to air	6%	Residues landfill	Nickel[b], to water	2%
	Infrastructure	Chromium VI, to air	5%			
AL	Sanitary landfill	Barium[c], to water	24%	Sanitary landfill	Nickel[b], to water	40%
	Infrastructure	Chromium VI, to air	17%	Sanitary landfill	Barium[c], to water	11%
	External energy	Benzene, to air	9%	Wastewater treatment	Nickel, to water	6%
	Residues landfill	Nickel[b], to soil	7%	Sanitary landfill	Copper[b], to water	6%

[a] Emission due to plastic and inert metal fractions in medical waste
[b] Emission due to inert metal fractions in medical waste
[c] Emission due to glass and inert metal fractions in medical waste
[d] Emission due to rubber and plastic fractions in medical waste

long-term time frame. The non-incineration alternatives yielded similar results, with sanitary landfill showing the largest contribution to HT. Further, we performed a perturbation analysis of dioxins with respect to HT for the HWI alternative. The multiplier 0.1 indicates that a 1% increase in dioxins leads to an increase of about 0.1% in the HT indicator. However, it should be noted that this result could involve large uncertainties. From a methodological point of view, the characterization models contain many assumptions. From a data point of view, the HWI model regards the dioxin emission as a process-specific burden, whose value is assumed to be the legal limit and do not rely on actual measurements. Despite these uncertainties, we believe it is better to try to discuss this issue in LCA than to merge it in the impact assessment. For FAET, heavy-metal emissions are completely dominant. In the short-term, the incineration process is the key source of heavy-metal emissions to water.

4.2.3 Eutrophication

The characterization results (see Fig. 3) for eutrophication show significant differences between the alternatives; and incineration alternatives are better than non-incineration alternatives. The contribution analysis for eutrophication in short-term is shown in Fig. 6. Nearly 100% of the contribution to eutrophication comes from NH_4^+, PO_4^{3+}, and NO_3^- emissions to freshwater in sanitary landfill process associated with non-incineration alternatives. On the other hand, the HWI process dominates eutrophication in incineration alternatives. The probable reason is the difference in the fate of the N between the HWI and sanitary landfill processes. In the HWI process, 98.9% of N is transferred to gas, 1% to slag, and 0.1% to water. In the sanitary landfill process, 28% of N is transferred to short-term leachate, 2% to gas, and 70% to the long-term leachate. In this study, HWI with a $DeNO_x$ stage is inventoried, which means most of air-bound N is converted to harmless N_2.

5 Conclusions and recommendations

In the present study, life cycle assessment was used to compare incineration and non-incineration treatments for medical waste. Although the assumptions about the time frame for landfill markedly influenced the impact category scores, both time frames led to a virtually identical order of preference. HWI with high energy recovery is better in terms of AD, GW, OD, TET, POC, acidification, and eutrophication. Non-incineration alternatives cause higher eutrophication scores than incineration ones due to the difference in N element transformations. Characterization results indicate all environmental impacts could be significantly reduced by energy recovery in HWI process, while the influence of

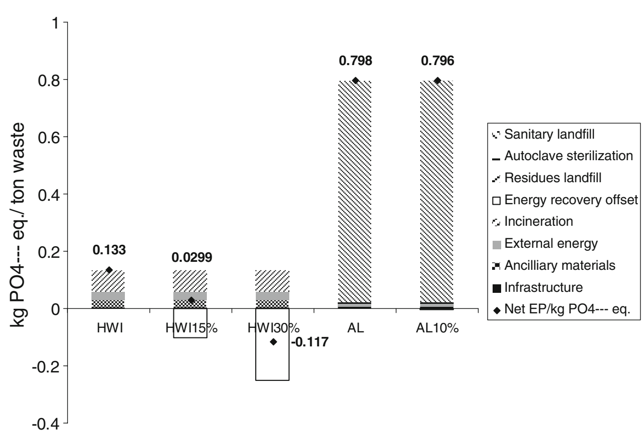

Fig. 6 Contribution analysis for eutrophication in short-term time frame

energy recovery in the non-incineration alternatives is slight. Generally, the conventional waste hierarchy, which implies incineration with energy recovery, is better than landfill, a fact which also applies in the case of medical waste. Under the short-term time frame assumption, the contribution analysis shows that the sanitary landfill process is the key issue in the non-incineration alternatives and dominates the total environmental burden. In the incineration alternatives, the HWI process contributes most to GW, FAET, and eutrophication, while residues landfill contributes most to HT. From a life cycle perspective, the dioxin emission in HWI is not the most relevant one to HT. However, it is necessary to keep in mind that the insufficient knowledge of mechanisms of dioxin formation and characterization methods could introduce uncertainty.

Although the discussion of other options is beyond the scope of this paper, it would be meaningful to extend the evaluation to other technologies, in order to construct a framework for medical waste management.

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